

**MIL03346**  
Clinopyroxenite  
715 grams



**Figure 1:** MIL03346 on ice “let’s come back next year and look for the rest of it”.



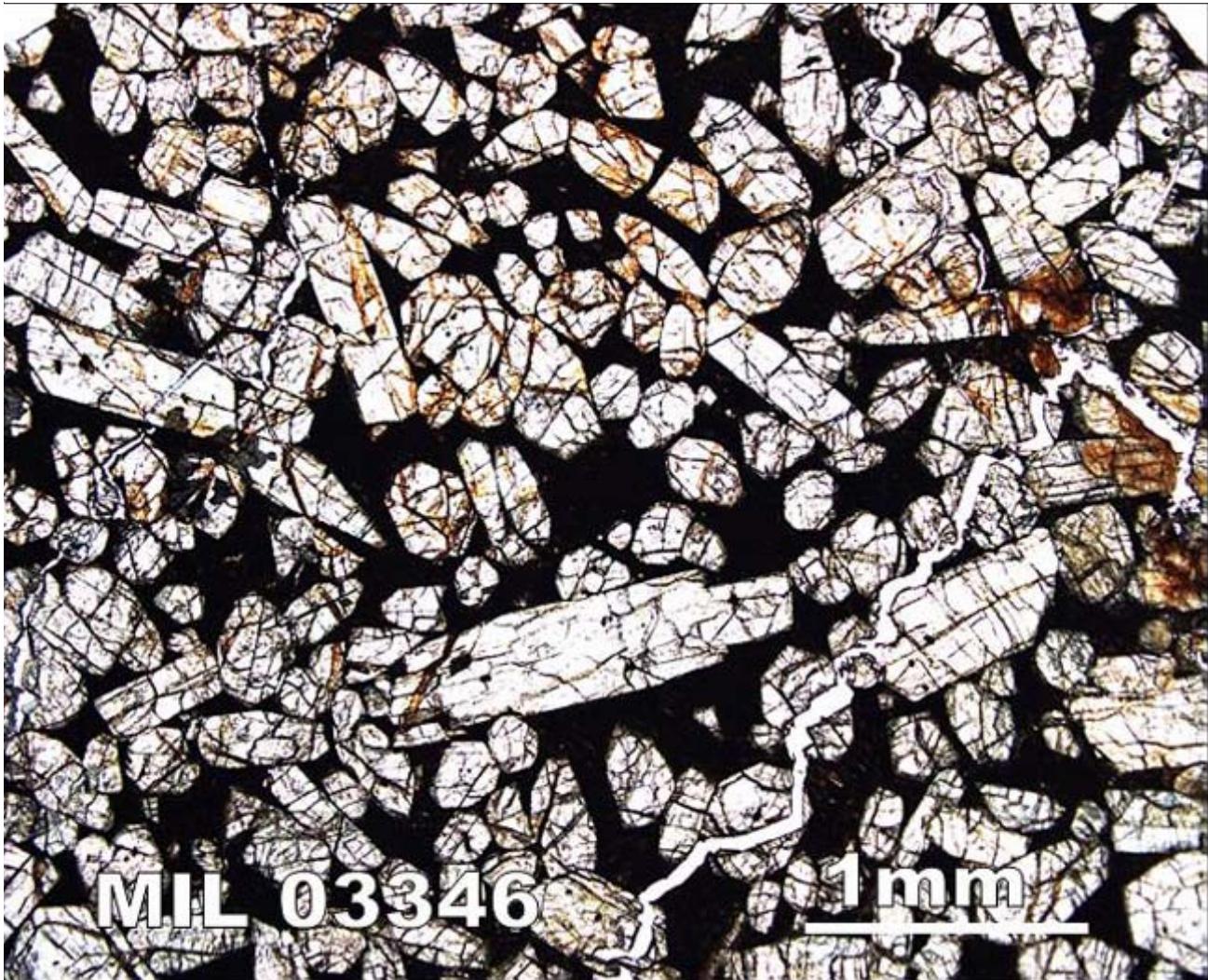
**Figure 2:** Initial processing photo of MIL 03346. Cube is 1 cm. for scale. Photo is from newsletter.

### **Introduction**

The Mars Exploration Program supplemented the 2003-2004 ANSMET expedition in the hope of improving the chance of finding additional samples of Mars, and, as luck would have it, a large nakhlite was recovered from the blue ice on Dec 15, 2003 in the Miller Range, among the other 1358 new specimens discovered during this field season (Satterwhite and Righter 2004).

<http://geology.cwru.edu/~ansmet/>

About 60 % of the surface of MIL 03346 was covered with a black, wrinkled fusion crust (figure 1). MIL 03346 is a nakhlite with abundant clinopyroxene and rare olivine set in a fine-grained mesostasis with some alteration (figure 2). It is apparently part of the same lava flow as the other nakhlites, but has had a faster cooling history (Day *et*



**Figure 3:** Thin section photomicrograph of MIL03346. Scale bar is 1 mm. Euhedral clinopyroxene is set in fine-grained mesostasis (opaque). Areas of apparent alteration are present. Photo is from newsletter.

al. 2006). It has a high proportion of glassy mesostasis, with some pre-terrestrial alteration (figure 3).

MIL03346 has been measured as 1.3 to 1.4 b.y. old, and has an exposure to cosmic rays of ~ 10 m.y.

### Petrography

MIL 03346 (MIL for short) is a cumulate of abundant elongate clinopyroxene (0.2 to 2.5 mm) and minor

olivine crystals (up to 1.7 mm) set in a dark-colored, fine-grained intercumulate mesostasis (Stopar *et al.* 2005; McKay and Schwandt 2005; Mikouchi *et al.* 2005; Rutherford *et al.* 2005; Day *et al.* 2006 and Imae and Ikeda 2007). Stopar *et al.* and Day *et al.* compared the grain size distribution of MIL with that of the other clinopyroxenites, finding that it had the largest average crystal size (0.43 x 0.26 mm).

### Mineralogical Mode for MIL 03346

	Stopar et al. 2005	Rutherford <i>et al.</i> 2005	McKay and Schwandt 05	Anand et al. 2005	Mikouchi et al. 05	Day et al. 06	Imae and Ikeda 07
Olivine	2 vol. %	tr.	4.6		4	1.1	0.8
Pyroxene	78	65	79.8	75	74	78.4	67.7
Plagioclase						0.1	
Mesostasis	19	35	15.7	25	22	19.8	31.5
Opques “alteration”	0.9		0.9			1	0.24

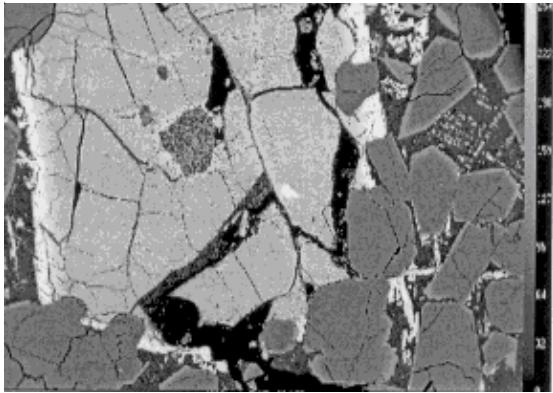


Figure 4: BSE image of large olivine (500 microns) with Fe-rich rim (from Rutherford et al. 2005).

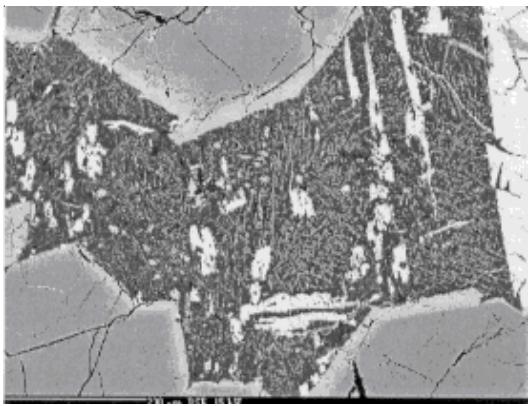


Figure 5: BSE image of matrix of MIL 03346 showing skeletal magnetite and also Fe-rich rim on euhedral clinopyroxene (Rutherford et al. 2005).

Magmatic melt inclusions are reported in the olivine (Rutherford et al. 2005) and in augite (Imae and Ikeda 2007). Various phases, including jarosite, saponite and Cl-rich amphibole, have been reported in these melt inclusions (McCubbin et al. 2008; Imae and Ikeda 2007; Sauter et al. 2006). Imae and Ikeda calculate the composition of the trapped (parental) magma from these melt inclusions.

The mesostasis (figure 5) consists of a dendritic intergrowth of fayalite, ferro-hedderbergite, Ti-magnetite, cristobalite, apatite and feldspar glass (similar to that of NWA 817). No plagioclase has been found in MIL. Day et al. (2005, 2006) conclude that MIL is part of the same cumulate-rich lava flow as the other nakhlites, but that it experienced less equilibration and faster cooling than the other nakhlites.

Olivine has “iddingsite-smectite”(?) alteration in cracks, similar to that found in the other nakhlites

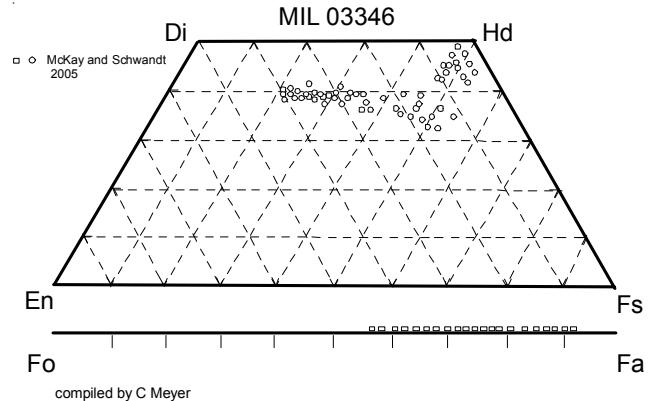


Figure 6: Pyroxene and olivine compositions of MIL 03346 (from McKay and Schwandt 2005).

(Armand et al. 2005, Stopar et al. 2005). Mikouchi et al. (2005) note that the alteration in MIL 03346 (Antarctica) is similar to that in NWA 817 (Sahara Desert) and that this might indicate the alteration is pre-terrestrial. Stopar et al. (2005) report that “gypsum is found in cracks, voids and veins throughout the thin sections.” Sauter et al. (2005, 2007) report Cl-rich amphibole, chlorite, phosphaste and a “mixed sulfate of Fe and S” which they interpret as derived from a soil component on Mars. Day et al. (2006) find that this alteration assemblage in MIL03346 is probably a sub-micrometer mixture of smectite clay, iron oxyhydroxides and salt minerals, with up to 14 wt. % H<sub>2</sub>O (as OH groups).

## Mineral Chemistry

**Olivine:** MIL has less olivine (3%) than the other nakhlites (Day et al. 2006). McKay and Schwandt (2005) found that large olivine grains (up to 1.7 mm) have uniform cores Fo<sub>44-43</sub>, but zone to Fo<sub>5</sub> at their outer rims (figure 4). Tiny skeletal fayalite is found in the mesostasis.

**Pyroxenes:** Cores of clinopyroxene cluster around Wo<sub>39</sub>En<sub>27</sub>. The rims zone increase in Fe and decrease in Ca to ~Wo<sub>34</sub>En<sub>14</sub>. Mikouchi et al. (2005), Anand et al. (2005) and McKay and Schwandt (2005) found that the outer rims, adjacent to the mesostasis, zone to ferro-hedderbergite (figure 6). Imae and Ikeda found that the outer rims of pyroxene pheocrysts contain up to 10 wt.% Al<sub>2</sub>O<sub>3</sub>. Domeneghetti et al. (2006) found the iron in MIL was oxidized (Fe<sup>+3</sup>).

**Ti-magnetite:** Dendritic chains of Ti-magnetite are prevalent in the mesostasis (similar to NWA 817). Day et al. (2006) determined that magnetite was chemically

zoned from pur magnetite towards ulvöspinel. Both Dyar *et al.* (2006) and Morris *et al.* (2006) reported magnetite in their Mossbauer spectra.

**Glass:** Feldspathic-glass compositions in the mesostasis are  $\text{An}_{29-38}\text{Or}_{7-14}$  (Anand *et al.* 2005; Day *et al.* 2006).

**Silica:** Anand *et al.* (2005) and Mikouchi *et al.* (2005) report small (5 micron) blebs of silica in the mesostasis. Chennaoui Aoudjehane *et al.* (2006) used cathodoluminescence to study shock effects.

**Amphibole:** Sautter *et al.* (2006, 2007) reported the presence of Cl-rich amphibole (1.5 to 7% Cl) in melt inclusions in augite and in olivine.

**Phosphates:** Fries *et al.* (2006) studied phosphates in MIL03346 by confocal Raman imaging techniques and found that they were “hydrated”.

**Sulfides:** Day *et al.* (2006) find that sulfide “blebs” are pyrrhotite – often altered.

**Jarosite:** The Martian sulfate mineral jarosite has been discovered in melt inclusions in augite (McCubbin *et al.* 2008) and in the interstices of MIL03346 (Vicenzi *et al.* 2007).

**Saponite ?** Imae and Ikeda (2007) reported an occurrence of a hydrated phase (saponite?), adjacent to fayalite, in a trapped melt inclusion – suggesting that the alteration occurred on Mars.

## Whole-rock Composition

The whole rock composition has been determined by Anand *et al.* (2005), Barret *et al.* (2006) and Day *et al.* (2006) (table 1). Barret et al. found that Co, Ni, Cu and Zn were similar to other nakhrites. The large ion lithophile elements are similar to, but elevated, compared with Nakhla (figure 7). Note the lack of any Eu anomaly. Dreibus *et al.* (2006) reported 147 ppm F, 248 ppm Cl, 0.45 ppm Br, 610 ppm S and 315 ppm carbon. Shirai and Ebihara (2008) have also analyzed MIL03346 (data reported in diagrams).

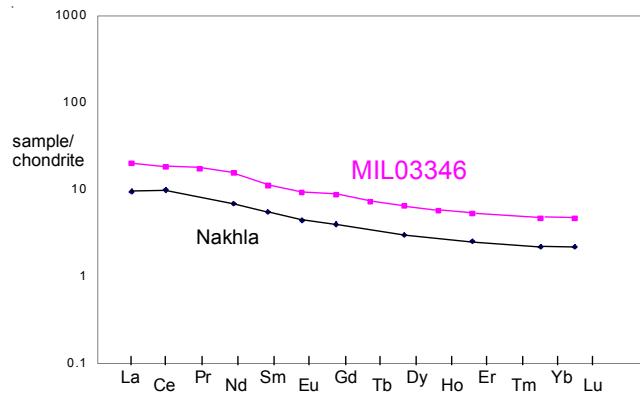


Figure 7: Normalized rare-earth-element pattern for MIL03346 compared with that of Nakhla. Data from Barrat *et al.* 2006 and Nakamura *et al.* 1973.

## Radiogenic Isotopes

Murty *et al.* (2005) determined a U, Th-<sup>4</sup>He age of  $1.02 \pm 0.15$  b.y. and K-Ar age of  $1.75 \pm 0.26$  b.y. (based on U, Th, K contents of Nakhla!). Bogard and Garrison (2006) determined an Ar plateau age of  $1.44 \pm 0.02$  m.y. (figure 8). Shih *et al.* (2006) determined a Rb-Sr isochron of  $1.29 \pm 0.12$  and a Sm-Nd isochron of  $1.36 \pm 0.03$  b.y. (figures 9 and 10).

## Cosmogenic Isotopes

Murty *et al.* (2005) determined an average exposure age of  $9.5 \pm 1.0$  m.y. for MIL 03346.

## Other Studies

Oxygen isotopes are not reported.

Wadhwa and Borg (2006) found that the <sup>142</sup>Nd and <sup>182</sup>W isotopic anomalies were similar to other nakhrites, concluding that nakhrites formed under relatively oxidizing conditions.

Murty *et al.* (2005) reported the isotopic ratios of rare gases extracted at different temperatures from MIL 03346.

Dyar *et al.* (2005) determined the Mossbauer, reflectance and thermal emission spectra of MIL03346 (figures 11, 12 and 13), claiming that this rock is highly oxidized with abundant Fe<sup>3+</sup>. Roechette *et al.* (2005) reported the magnetization.

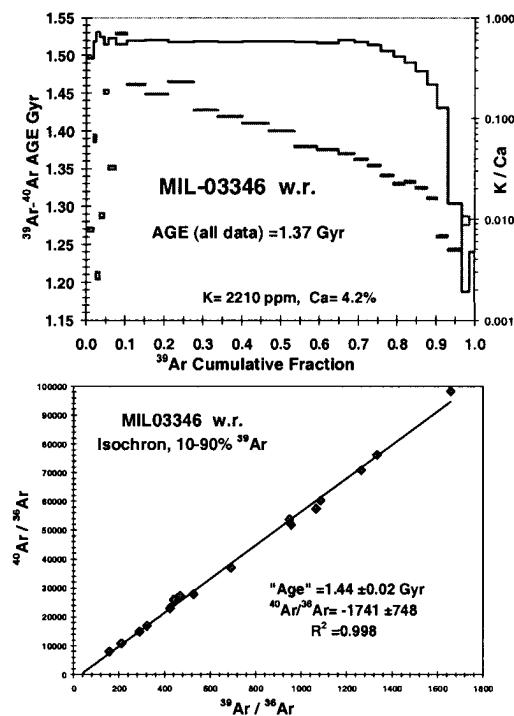


Figure 8: Ar/Ar age dating of MIL03346 by Bogard and Garrison 2006.

### Processing

During initial processing, a 1 cm thick slab was cut through the center of MIL 03346 (figure 14) (McBride *et al.* 2005). About 45 thin sections were prepared and allocated (see diagram).

MIL 03346 was examined and split in dry-nitrogen glove boxes at JSC which have been thoroughly cleaned and dried immediately before processing of this sample. The sample was only exposed to stainless steel, aluminum and Teflon, although the gloves, gaskets and band saw wheels are made of Neoprene and/or Viton. However, the sample itself was only handled with Teflon overgloves.

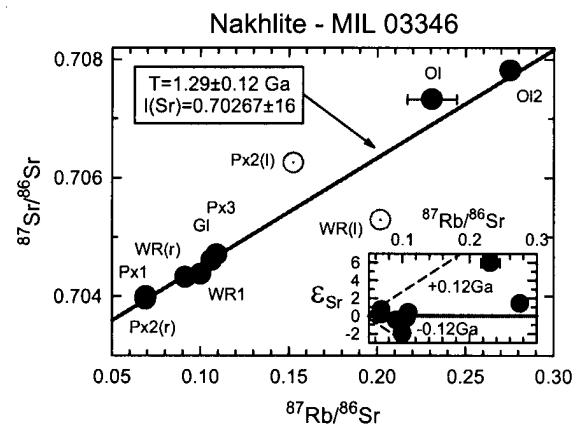


Figure 9: Rb-Sr isochron diagram for MIL03346 by Shih *et al.* 2006.

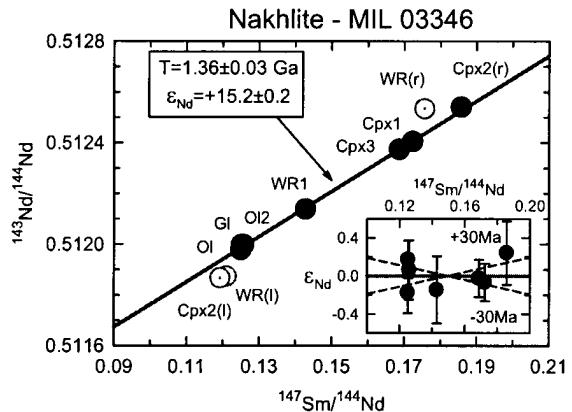


Figure 10: Sm-Nd isochron diagram for MIL03346 by Shih *et al.* 2006.

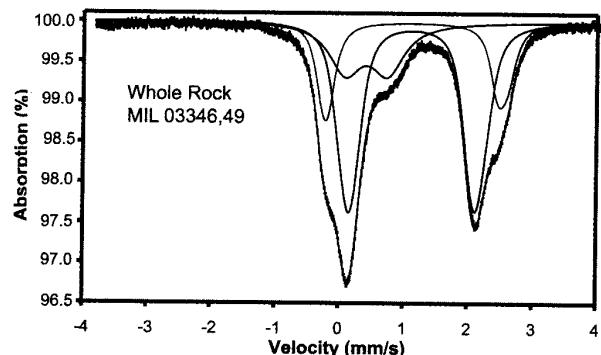


Figure 11: Mossbauer spectra of MIL03346 from Dyar *et al.* 2006.

### Age data for MIL03346

	Ar/Ar
Bogard and Garrison 2006	1.44 ± 0.02 b.y.
Shih <i>et al.</i> 2006	

Rb/Sr	Nd/Sm
1.29 ± 0.12	
	1.36 ± 0.03

**Table 1. Chemical composition of MIL 03346.**

reference	Anand2005	Barret2006	Day2006
SiO <sub>2</sub> %	49.2		49.5 (b)
TiO <sub>2</sub>	0.07	0.69 (a)	0.68 (b)
Al <sub>2</sub> O <sub>3</sub>	3.59	3.66 (a)	4.09 (b)
FeO	19.23	19.12 (a)	19.1 (b)
MnO	0.45	0.46 (a)	0.46 (b)
MgO	9.33	9.99 (a)	9.26 (b)
CaO	15	15.75 (a)	14.4 (b)
Na <sub>2</sub> O	1.01	1 (a)	0.96 (b)
K <sub>2</sub> O	0.29	0.27 (a)	0.2 (b)
P <sub>2</sub> O <sub>5</sub>	0.22	0.25 (a)	0.23 (b)
S %			0.06 (b)
sum			
Sc ppm	46	54.5 (a)	52.9 (c)
V	184	208 (a)	210 (c)
Cr	1300	1192 (a)	1300 (c)
Co	25	35.7 (a)	38.7 (c)
Ni	60	49 (a)	58.1 (c)
Cu	13	8.2 (a)	13.3 (c)
Zn	65	61.3 (a)	61.5 (c)
Ga		6.51 (a)	6.77 (c)
Ge ppb			
As			
Se			
Rb		4.14 (a)	4.41 (c)
Sr	106	131.7 (a)	121.3 (c)
Y	7	8.44 (a)	8.5 (c)
Zr		23.29 (a)	21.2 (c)
Nb		3.98 (a)	3.65 (c)
Mo			
Ru			
Rh			
Pd ppb			
Ag ppb			
Cd ppb			
In ppb			
Sn ppb			
Sb ppb			
Te ppb			
Cs ppm		0.29 (a)	0.27 (c)
Ba	53	59.58 (a)	56.9 (c)
La		4.7 (a)	3.89 (c)
Ce		11.01 (a)	11.3 (c)
Pr		1.56 (a)	1.78 (c)
Nd		7.07 (a)	8.04 (c)
Sm		1.64 (a)	1.83 (c)
Eu		0.522 (a)	0.52 (c)
Gd		1.73 (a)	1.86 (c)
Tb		0.266 (a)	0.3 (c)
Dy		1.57 (a)	1.66 (c)
Ho		0.317 (a)	0.32 (c)
Er		0.851 (a)	0.84 (c)
Tm			0.13 (c)
Yb		0.766 (a)	0.8 (c)
Lu		0.114 (a)	0.13 (c)
Hf		0.69 (a)	0.66 (c)
Ta		0.23 (a)	0.21 (c)
W ppb		0.4 (a)	
Re ppb			
Os ppb			
Ir ppb			
Pt ppb			
Au ppb			
Th ppm		0.42 (a)	0.43 (c)
U ppm		0.09 (a)	0.11 (c)
technique:	(a) ICP, (b) e.probe (c) ICP-MS		

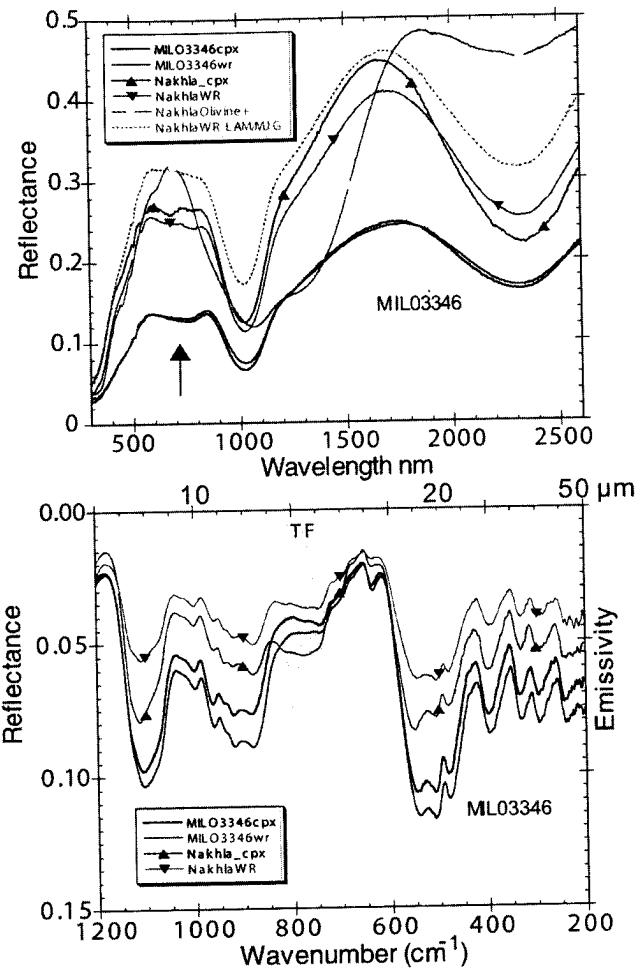


Figure 12: IR-visible-UV reflectance spectra for MIL03346 (dominated by clinopyroxene) from Dyar et al. 2006.

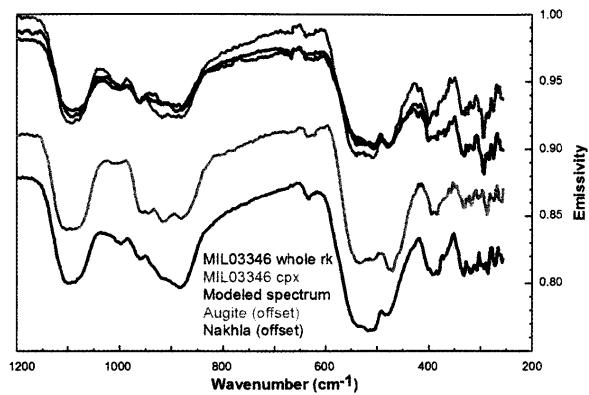
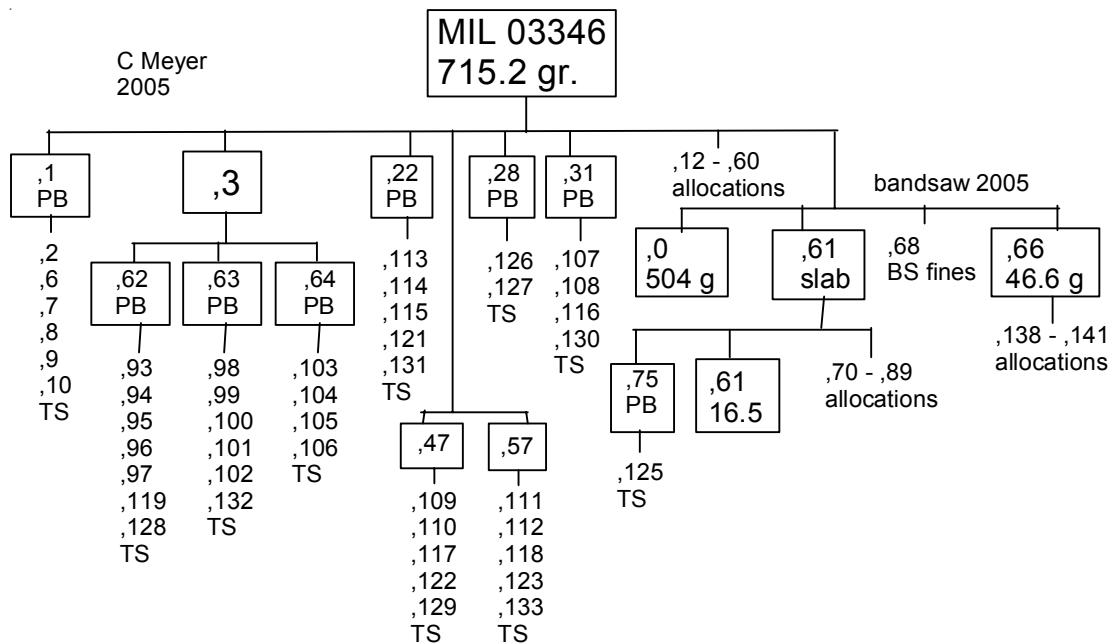


Figure 13: Thermal emission spectra of MIL03346, Augite and Nakhla from Dyar et al. 2006.



Figure 14: Sawn surfaces of MIL03346,66 and slab .61. Scale is in cm. (photo courtesy of Kathleen McBride).



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